Multicriteria decision analysis applied to cover crop species and cultivars selection

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A B S T R A C T

Cover crop selection should be oriented to the achievement of specific agrosystem benefits. The cover crop, catch crop, green manure and fodder uses were identified as possible targets for selection. The objective was to apply multi-criteria decision analysis to evaluate different species (*Hordeum vulgare* L., *Secale cereale* L., ×*Triticosecale* Whim, *Sinapis alba* L., *Vicia sativa* L.) and cultivars according to their suitability to be used as cover crops in each of the uses. A field trial with 20 cultivars of the five species was conducted in Central Spain during two seasons (October–April). Measurements of ground cover, crop biomass, N uptake, N derived from the atmosphere, C/N, dietary fiber content and residue quality were collected. Aggregation of these variables through utility functions allowed ranking species and cultivars for each usage. Grasses were the most suitable for the cover crop, catch crop and fodder uses, while the vetches were the best as green manures. The mustard attained high ranks as cover and catch crop the first season, but the second decayed due to low performance in cold winters. Mustard and vetches obtained worse rankings than grasses as fodder. Hispanic was the most suitable barley cultivar as cover and catch crop, and Albacete as fodder. The triticale Titania attained the highest rank as cover and catch crop and fodder. Vetches Aitana and BGE014897 showed good aptitudes as green manures and catch crops. This analysis allowed comparison among species and cultivars and might provide relevant information for cover crops selection and management.

Keywords:
Catch crop
Green manure
Fodder
Ground cover
Dietary fiber
Crop selection

1. Introduction

Cover crops selection is oriented to the achievement of goals related to the ability of the crops to provide benefits such as the soil erosion control (Bowman et al., 2000), prevention of winter nutrient leaching (Gabriel et al., 2012) and the supply of organic matter to the soil (Kuo et al., 1997) defined as ecosystem services (Diaz et al., 2007). These benefits are required in different combinations and degrees according to the particular needs of the farmer and the agrosystem. We can distinguish between cover crops, catch crops and green manures according to the specific function developed by the culture in the system. Cover crops are mainly introduced to control the soil erosion pursued by water and wind. However, in some countries, they can be also used to increase the water storage and the sowing opportunity (Clark et al., 1997). When sowing catch crops the objective is to absorb in the vegetal biomass a specific compound contained in the soil, so the pollutant effect is controlled. Green manures perform as nutrient source for the following crop. Green manuring commonly involves the introduction of legumes because of their N fixation, accompanied by the recycling of other nutrients absorbed during the green manure growth period. Fodder production is another possible outcome for cover cropping that may result in an economical benefit for the farmer, even larger than the fertilizer savings attributed to green manuring (Gabriel et al., 2013). It should be stressed that one particular cover crop is able to provide more than one function in the system along its cycle. The capability of a specific cover crop to provide the above mentioned benefits will depend on characteristics of its growth pattern, nutrient exchange or residue quality that can be related with quantitative variables and subsequently characterized and compared (Ramírez-García et al. 2012). There are few attempts

Abbreviations: ADF, acid-detergent fiber; AHP, analytic hierarchy process; BM, above-ground biomass; CN, C:N ratio; DFC, dietary fiber content; ELECTR, Elimination and choice translating algorithm; GC, ground cover; L, lignin; MCDA, multicriteria decision analysis; NDF, neutral-detergent fiber; N_{dfa}, N derived from the atmosphere; N_{upt}, N uptake; RQ, residue quality.

in the literature to assess the variables that characterize the cover crops features (Bodner et al., 2010) and to orient cover crops' selection to targeted functions (Jannoyer et al., 2011). Thus, methods allowing the comparison of different cover crop species and cultivars according to the ecosystems services provided may be useful for farmers, breeders and researchers.

Multicriteria decision analysis (MCDA) techniques are applied as an aid for the selection of alternatives in the presence of multiple criteria, usually with conflicting objectives (Zeleny, 1982). Taxonomic classifications of MCDA methodologies can be helpful guiding the decision makers when choosing or combining (mixed methods) the available MCDA techniques (Zanakis et al., 1998; Sadok et al., 2008). The MCDA consists, without regard of the particular method applied, in four steps: (i) structuring the hierarchy of the problem, (ii) establishing the aggregation rules, (iii) aggregating the attributes, and (iv) obtaining ordered alternatives (Guitouni and Martel, 1998). In the agricultural context, Rehman and Romero (1993) reviewed the application of MCDA techniques to the management of agricultural systems and since then, they have been applied to a wide range of topics such as the decision making process in water management policy (Gómez-Limón and Berbel, 2000), the evaluation of the sustainability of different agricultural managements (Sadok et al., 2008) or the farm production planning (Ortuño and Vitoriano, 2011). Continuing under the scope of agriculture, only few studies concerning the choice of species or cultivars have been conducted under different MCDA strategies, mainly under discrete outranking methods. The ELECTRE (elimination and choice translating algorithm) method was developed over more than 30 years by Roy (1993)), and applied by Roudeillac et al. (1997) and Diaby et al. (2010) for strawberry and rubber tree varieties selection, respectively. Other authors like Srdjevic et al. (2004) evaluating walnut cultivars, or Li et al. (2011) selecting *Lilium* species and clones, obtained ranked ordinations of the alternatives assessed after applying an analytic hierarchy process (AHP) to both quantitative and qualitative data. Similarly, Pavlovic et al. (2011) used only qualitative attributes to rank a list of hop hybrids through the DEX method, which combines the problem structuration of AHP with elements of expert systems and machine learning. All those studies included the assessment of experts deciding not only the weights of the variables selected, but in some cases also the values of the attributes attained by the alternatives. As the comparison of species and cultivars to act as cover crops involved different combination of attributes, we choose the weighted average approach, which aggregates multiple criteria into overall values by multi-attribute utility functions (Hayashi, 2000). The performance of an alternative (i.e. a cultivar to act as a cover crop) is the result of the weighted sum of the values attained for each attribute. As this is a compensatory method, it is admitted that an absolute compensation between the different attributes can exist. Thus, a good performance on one attribute can easily counterbalance a poor one on another (Guitouni and Martel, 1998). The global performance may be used to make a ranking among all the alternatives.

In this framework, the objective of our study was to evaluate different species (i.e. barley, rye, triticale, mustard and vetch) according to their suitability to be used as cover crops in each of their specific modalities (cover crop, catch crop, green manure and fodder), as well as for selected cultivars of each species by applying a multi-criteria decision analysis. The rankings obtained may allow judging the performance of the attributes selected for the characterization of the crops studied and the aggregation method applied.

2. Materials and methods

The data collection was performed along two seasons (2010/2011 and 2011/2012) between the months of October and April (May) of the following year at the experimental farm of the Technical University of Madrid (Central Spain). The soil was a sandy loam formed by recent alluvial deposits. The pH (1 g soil/2.5 mL H_2O) was 8.57 and had a 2.20% of organic matter and 0.15% of N. Available P content was 60.4 mg/kg and K 520 mg/kg. The location has a Mediterranean semiarid climate with high interannual variability and a mean annual temperature of 14.6 °C. January monthly temperature of 6.1 °C is the lowest while July the highest with 24.8 °C. The average annual rainfall from October to April is 306 mm. Measurements of the main climate variables were recorded throughout the experiment at the field site (Fig. 1).

Twenty cultivars of five different species were sown within a randomized factorial design with three replications. Seven barley (*Hordeum vulgare* L.) cultivars from the Spanish barley core collection (Igartua et al., 1998) were selected based on their good soil coverage characteristics. These barley cultivars were: Albacete, Cierzo, CNE 73, CNE 81, Hispanic, Tardana and Valencia de Alcántara. Four triticale (×*Triticosecale* Whim) cultivars: Forricale, Montijano, Titania and Verato, were selected from GENVCE database, a Spanish group of breeders and researchers working on cereal varieties. The traditional rye (*Secale cereale* L.) cultivar Petkus was also included, as well as the mustard (*Sinapis alba* L. subsp. *mairei* (H. Lindb.) Maire) selected as a cover crop by IFAPA (Andalusia regional research institute) in Southern Spain (Alcántara et al., 2011). Seven vetch (*Vicia sativa* L.) cultivars were selected to assess variability in a legume crop: Aitana, Alcaraz, BGE014897, Castilla, Kira, Prontivesa and Verdor. Most of the vetches were selected based on cultivars commonly used in Spain, except BGE014897, which is an original entry from CNRF (Plant genetic resources center of Spain).

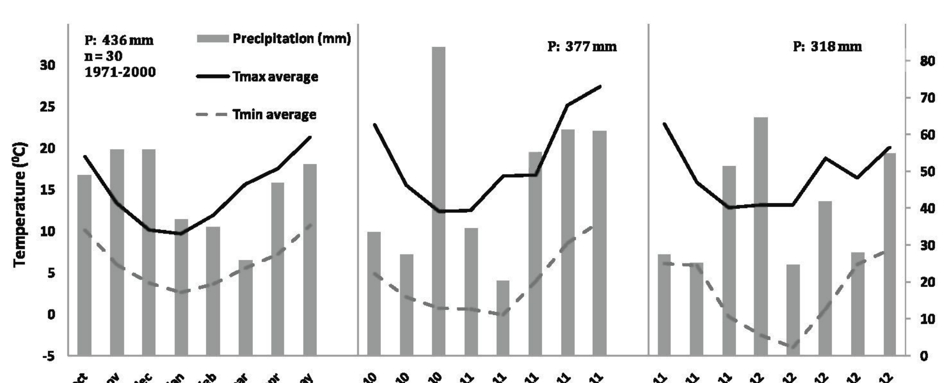

Fig. 1. Climatic data along the growth period of cover crops: (left) 30-year series from a near climatic station; (center) the first (2010–2011) and (right) the second (2011–2012) season of cover crops studies from a climatic station situated at the experimental site.

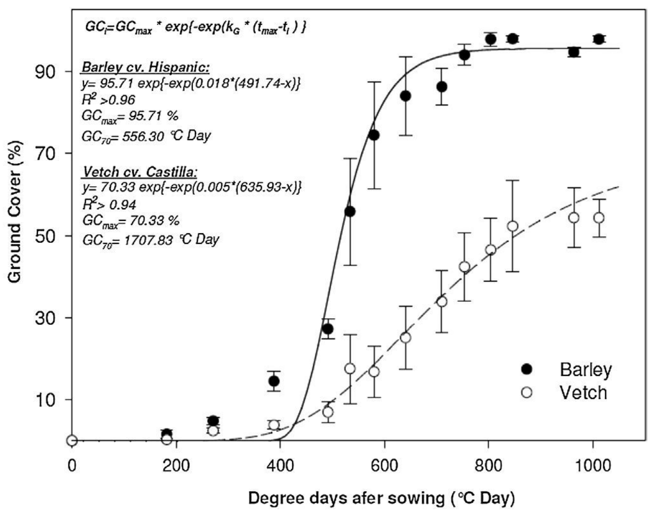

Fig. 2. Gompertz equations fitted for ground cover (%) evolution of two of the twenty cover crop cultivars studied in the season 2010–2011 (continuous line for the barley and dashed line for the vetch). The data was adjusted until the decay of ground cover (%) due to frosts (thermal time around 1000 DD). GC_i (%): ground cover (GC) at thermal time t_i (DD^{-1}); GC_{max} (%): maximum GC; k_G (DD^{-1}): weighted mean relative growth rate; t_{max} (DD): thermal time until growth rate is maximum; GC_{70}: thermal time until 70% GC is attained.

All plots were sown at the beginning of October (7 and 11, respectively for 2010 and 2011) at a density of 240 seeds/m^2 in rows separated 20 cm. Plot size was 2.4×7 m^2. Weed proliferation was controlled manually during all the experiment. The crops were grown until anthesis in grasses and flowering in vetch and mustard (GS-61, Lancashire et al., 1991).

The measured variables were the ground cover (GC), the biomass accumulation, the N uptake and the N derived from the atmosphere in the legume (N_{dfa}), the plant C:N ratio, the dietary fiber content and the crop residue quality. The GC was monitored during the whole crop cycle based on the analysis of digital images of a marked area (1.5×1.5 m^2) inside each plot, taken from a zenithal perspective at a 1.5 m height (Ramírez-García et al., 2012). Along the first (and the second) season, a total of 21 (22) sampling dates were analyzed for the GC. The GC data previous to the decay produced by the winter frosts was adjusted to a Gompertz model, which assumes a sigmoid growth until an asymptotic maximum value (Ramírez-García et al., 2015). This adjustment allowed obtaining two sub-attributes of GC for each cultivar: the thermal time until GC reached 70% (GC_{70}) (°C day), and its maximum value attained (GC_{max}) (%) (Fig. 2). The base temperature to calculate the degree days was 0 °C.

The other six variables were determined in homogeneous biomass subsamples harvested at the end of the experiment. Above-ground biomass (BM) was acquired by cutting the crops by hand at ground level in a 0.25×0.25 m^2 area. Samples were dried for 48 h at 65 °C and subsequently weighed to determine BM. The C and N concentrations were measured in a subsample by the Dumas method (LECO CHNS-932® Analyser, St. Joseph, MI, USA). The N_{dfa} in the vetch cultivars was estimated by the natural abundance method (Unkovich and Pate, 2001), based on the δ15N (‰) determination (Europa Scientific 20-20 IRMS Analyser®, Crewe, UK) on subsamples from the legumes and two reference crops (barley and mustard). The crop N content was calculated as the product of BM and N concentration. In non-legumes the N uptake (N_{upt}) was equal to the crop N content, while in the vetches was calculated as the difference between the N content and the N_{dfa}. Neutral detergent fiber (NDF), acid detergent fiber (ADF) and lignin (L) were determined by the Goering and van Soest method (1970), and dietary fiber content (%) calculated as the total fiber (NDF-L). The crop residue quality was calculated as the sum of its labile (100-NDF) and cellulose like (ADF-L) decomposable fraction (Quemada and Cabrera, 1995).

The attributes selected to be used in the MCDA were: the two GC sub-attributes, i.e. the thermal time until GC reached 70% (GC_{70}) (°C day) and the maximum GC attained (GC_{max}) (%)), the biomass at the end of the experiment (BM) (g/m^2), the C:N ratio (CN), the N uptake (N_{upt}) (%), the N derived from the atmosphere (N_{dfa}) (%), the residue quality (RQ) (%) and the dietary fiber content (DFC) (%).

The first step in the method was assigning a measured value to each alternative (cultivar) for each of the attributes involved in the analysis. Considering i = 1,2,. . .,20 cultivars evaluated by j = 1,2,. . .,7 attributes, we obtained 140 outcomes (20×7) R_{ij} that represented the value reached by the ith cultivar when it was evaluated through the jth cover crop attribute. The attributes were aggregated in utility functions where W_j was the weight assigned to each attribute and V_i the value attained by cultivar i:

$$V_i = \sum_{i=1}^{20} \sum_{j=1}^{7} \left(W_j \times R_{ij} \right) \quad \forall i, j \tag{1}$$

As the attributes were measured in different units, it was necessary to normalize the values before aggregating them. Normalization was performed following the process proposed by Diaz-Balteiro et al. (2011):

$$\bar{R}_{ij} = 1 - \frac{R_j^* - R_{ij}}{R_j^* - R_{*j}} = \frac{R_{ij} - R_{*j}}{R_j^* - R_{*j}} \quad \forall i, j \tag{2}$$

where $\bar{R}_{ij}$ was the normalized value attained by the ith cultivar evaluated through the jth attribute, R_j^* is the maximum or best value reached by the alternatives and R_{*j} the minimum or worst, if the attribute is of the type "more is better". In case the attribute falls in the category "less is better", R_j^* will be the minimum or best value, while R_{*j} the maximum or worst.

Hence, the decision makers (i.e. the authors) agreed the values that the weighting parameters W_j had to attain for each specific cover crop function. The scoring values were assigned depending on the relevance of each attribute to attain and specific function (Table 1).

The next step was to build the utility functions (Eq. (1)) assuming that the number of crosses assigned to each attribute in Table 1 was equal to the value of W_j. The addition of an attribute had a positive sign when the attribute was adding value to the particular function and negative when it was subtracting. The scoring assigned to the attribute GC was shared by its two sub-attributes GC_{70} and GC_{max},

Table 1
Importance of the normalized attributes in the cover crops utility functions assigned by the decision makers based on literature. x: somehow important; xx: important; xxx: very important; without mark: not relevant for that specific function. GC: ground cover; BM: biomass reached at the end of the experiment; CN: C/N relationship; N_{upt}: N uptake; N_{dfa}: N derived from the atmosphere; RQ: residue quality; DFC: dietary fiber content.

Use	Function	Requirements	GC	BM	CN	N_{upt}	N_{dfa}	RQ	DFC
Cover crop	Erosion control	Fast and high ground cover and slow decay residues	xxx	x	x			x	
Catch crop	Nutrient/pollutant uptake	High biomass accumulation and N uptake	x	xx	x	xxx		x	
Green manure	Nutrient supply	High N uptake and/or supply and easily decomposable residues		xx	x	x	xxx	x	
Fodder	Forage production	High biomass accumulation and dietary fiber content		xx	x	x	xx		xxx

being multiplied each of them by 0.5. The aggregation produced the following utility functions:

$$\text{Covercrop} = 3 \times \text{GC} + \text{BM} + \text{CN-RQ} \tag{3}$$

$$\text{Catchcrop} = \text{GC} + 2 \times \text{BM} - \text{CN} + 3 \times \text{N}_{\text{upt}} + \text{RQ} \tag{4}$$

$$\text{Greenmanure} = 2 \times \text{BM} - \text{CN} + \text{N}_{\text{upt}} + 3 \times \text{N}_{\text{dfa}} + \text{RQ} \tag{5}$$

$$\text{Fodder} = 2 \times \text{BM} - \text{CN} + \text{N}_{\text{upt}} + 2 \times \text{N}_{\text{dfa}} + 3 \times \text{DFC} \tag{6}$$

Once solved the four functions for each alternative, we obtained values that characterized the performance of the cultivars for each specific cover crop modality. The values were again normalized for the different cover crop modalities following the same procedure as in Eq. (2) to facilitate comparison and representation. Means and standard deviations of the three replicates for each cultivar were calculated to compare between cultivars. Means and standard deviations of the all cultivars and replicates for each species were calculated to compare between species. Finally, the results allowed the ranking in decreasing order of the species and the cultivars for each cover crop modality assessed, as well as the graphical representation through polar plots of the suitability of the alternatives to be used as cover crop, catch crop, green manure and fodder, respectively.

Statistical differences between species and cultivars were compared by means of the Tukey test ($p < 0.005$).

3. Results

3.1. Weather influence on the results

During the two seasons climatic conditions were favourable for cover crop growth (Fig. 1). From October to April 316 mm rainfall was accumulated along the first season, and 263 in the same period of the second. The temperature followed a classic Mediterranean distribution showing mild mean winter temperatures (10.2 °C the first season and 9.6 °C the second) alternated with occasional frosts that limited plant growth. The differences found in the intensity and the frequency of these frosts between the two seasons influenced the values attained by the alternatives in the growth attributes (i.e. GC and BM) (Table 2). The second winter was cooler than the first, being the mean temperatures between January and April between 4 and 5 °C lower the second season compared to the first. Low temperatures affected less the grasses than the mustard and the vetches. The cold effect on the grasses slightly decreased GC and BM in most of the cereal cultivars in the second season compared to the first; whereas, drastically reduced the GC and BM in the mustard and the legumes in the second season. Overall, the growth of the grasses was similar in both seasons, whereas the mustard and vetches were strongly affected by differences in weather conditions.

3.2. Species comparison

Grasses were the most suitable for the cover crop, catch crop and fodder uses, while the vetches were the best as green manures (Table 3). On the contrary, the vetches ranked in the last places for the cover crop usage and performed poorly as catch crop in both seasons. The mustard attained high ranks as cover and catch crop the first season, overcoming the barleys and triticales, but the second season decayed due to a low performance in cold winters. Mustard and vetches obtained the worst ranking value as fodder, while the rye the best. Rye performed also as the best catch crop.

3.3. Cultivar comparison

Based on the values attained for the various cover crop utility functions (Table 4), cultivars were ranked in descending order of their ability to control soil erosion, act as a catch crop or as green manure, and provide fodder (Table 5).

Barley cultivars ranked always in optimal positions as cover crops and were less suitable as green manures (Tables 4 and 5). Cierzo, Hispanic, CNE 73 and Albacete cultivars featured in the top 5 positions as cover crops in both years, while Valencia de Alcántara was always the worst of the barleys. Hispanic performed very well also as catch crop in the season 2011–2012 attaining the first position of all cultivars, but not as good the previous season, due to lower BM and a higher CN values (Table 2). Valencia de Alcántara and Tardana ranked in the last catch crop positions for barleys. CNE 73 and Hispanic reached the highest values of the barley cultivars as green manures, while Valencia de Alcántara and Tardana the lowest.

The best ranked barley cultivars in the fodder category within the two years studied were Albacete and CNE 73, which attained always a normalized utility function value above 0.56; while CNE 81 was the worst, with values below 0.55.

Triticale cultivars were located in the middle positions of the ranking, performing slightly better as cover crop and fodder than as catch crop or green manure. Three of the cultivars (particularly, Titania) increased their values the second year compared to the first, mainly due to an increase in BM, while Verato was more stable within years. Titania was above the 10th position in both years being the first cover crop of the triticales, while the last of them was Verato. Titania attained the highest values and ranks as catch crop, especially the second year, while Forricale the lowest. The triticales did not perform well as green manures, reaching the highest values Titania with 0.34 in 2012 and the lowest Forricale with a maximum of 0.15. Titania and Verato were the most suitable cultivars for being used as fodder, while Forricale and Montijano the less.

The vetches were highly ranked as green manures, but attained the lowest positions in the rest of cover crop modalities, probably due to its limited GC and BM. The variety BGE014897 showed a high aptitude as a cover crop in both seasons, which may be interesting for a vetch crop. Aitana and BGE014897 were the highest ranked vetches to be used as catch crops and green manures as they attained the highest BM. Aitana was also placed in a high rank as fodder compared with the rest of the vetch cultivars. Finally, Alcaraz showed its low suitability to any of the cover crop functions.

The polar plots showed the suitability of the barley as a cover crop and the vetch as green manure (Fig. 3). They also helped to emphasize the different degree of variability within species: while all the barley cultivars behaved in a similar way for the various cover crop functions, the vetch cultivars performed differently.

4. Discussion

Application of the MCDA weighted average approach allowed ranking the performance of the various species and cultivars according to their ability to accomplish several of the main cover crop functions. The ranking is in agreement with the literature reviewed, being grasses more suitable for erosion control and act as a catch crop whereas legumes for green manure (Langdale et al., 1991; Quemada and Cabrera, 2004; Bodner et al., 2010; Gabriel and Quemada, 2011). Therefore, the selected attributes characterized properly the cover crops and were sensitive to differences in their performance. In our study, the climatic differences between years affected the growth of mustard and vetch crops and subsequently the values of some of the attributes studied. For instance, the vetches suffered considerable damages due to low temperatures

Table 2
Normalized values attained by each cultivar for the attributes considered in the seasons 2010–2011 and 2011–2012. Standard deviations between parentheses. GC: ground cover; BM: biomass reached at the end of the experiment; CN: C:N relationship; N_{upt}: N uptake; N_{dfa}: N derived from the atmosphere; RQ: residue quality; DFC: dietary fiber content. In bold, the maximum values, and in italics, the minimum.

Species	Cultivars	GC_{70}	GC_{max}	BM	CN	N_{upt}	N_{dfa}	RQ	DFC	GC_{70}	GC_{max}	BM	CN	N_{upt}	N_{dfa}	RQ	DFC
		2010–2011								2011–2012							
Barley	Albacete	0.74 (0.19)	0.97 (0.03)	0.47 (0.09)	0.44 (0.15)	0.42 (0.11)	*0.00* (0.00)	*0.08* (0.07)	0.85 (0.13)	0.86 (0.03)	**0.99** (0.01)	0.61 (0.13)	0.55 (0.03)	0.17 (0.01)	*0.00* (0.00)	*0.10* (0.10)	0.66 (0.11)
	Cierzo	0.88 (0.11)	0.98 (0.01)	0.47 (0.09)	0.69 (0.07)	0.25 (0.03)	*0.00* (0.00)	0.12 (0.03)	0.86 (0.03)	0.92 (0.06)	0.96 (0.04)	0.66 (0.12)	0.62 (0.18)	0.10 (0.02)	*0.00* (0.00)	0.21 (0.02)	0.66 (0.00)
	CNE 73	0.93 (0.03)	0.99 (0.01)	0.34 (0.06)	0.40 (0.02)	0.44 (0.02)	*0.00* (0.00)	0.14 (0.05)	0.78 (0.07)	0.94 (0.03)	0.97 (0.01)	0.79 (0.09)	0.58 (0.05)	0.14 (0.03)	*0.00* (0.00)	0.43 (0.02)	0.60 (0.03)
	CNE 81	0.69 (0.29)	0.98 (0.01)	0.42 (0.07)	0.65 (0.31)	0.31 (0.14)	*0.00* (0.00)	0.23 (0.03)	0.77 (0.04)	0.83 (0.12)	0.95 (0.06)	0.62 (0.14)	0.66 (0.14)	0.12 (0.05)	*0.00* (0.00)	0.30 (0.06)	0.69 (0.04)
	Hispanic	0.87 (0.13)	0.97 (0.03)	0.43 (0.15)	0.61 (0.05)	0.29 (0.03)	*0.00* (0.00)	0.27 (0.05)	0.73 (0.06)	**0.96** (0.05)	0.95 (0.02)	0.78 (0.19)	0.38 (0.10)	0.24 (0.09)	*0.00* (0.00)	0.18 (0.03)	0.63 (0.16)
	Tardana	**0.96 (**0.03)	0.99 (0.01)	0.40 (0.01)	0.69 (0.06)	0.31 (0.10)	*0.00* (0.00)	0.18 (0.06)	**0.88** (0.01)	0.83 (0.06)	0.90 (0.05)	0.59 (0.27)	0.65 (0.17)	0.09 (0.10)	*0.00* (0.00)	0.37 (0.01)	0.56 (0.03)
	V. Alcantara	0.78 (0.11)	0.95 (0.00)	0.29 (0.07)	0.58 (0.10)	0.32 (0.06)	*0.00* (0.00)	0.20 (0.06)	0.77 (0.05)	0.59 (0.29)	0.92 (0.04)	0.59 (0.12)	0.63 (0.07)	0.13 (0.03)	*0.00* (0.00)	0.24 (0.17)	0.76 (0.07)
Rye	Petkus	0.47 (0.08)	0.99 (0.02)	**0.67** (0.30)	0.35 (0.09)	0.51 (0.11)	*0.00* (0.00)	0.49 (0.24)	0.74 (0.02)	0.89 (0.07)	0.96 (0.04)	0.75 (0.03)	0.40 (0.06)	0.28 (0.05)	*0.00* (0.00)	0.11 (0.00)	**0.81** (0.00)
Mustard	ssp. mairei	0.82 (0.11)	0.93 (0.01)	0.34 (0.17)	0.07 (0.01)	**0.95** (0.07)	*0.00* (0.00)	**0.92** (0.07)	*0.03* (0.02)	*0.00 (0.00)*	0.31 (0.17)	0.05 (0.03)	*0.05* (0.07)	**0.79** (0.29)	*0.00* (0.00)	**0.75** (0.35)	0.27 (0.18)
Triticale	Forricale	0.40 (0.11)	0.93 (0.05)	0.31 (0.01)	0.58 (0.03)	0.32 (0.04)	*0.00* (0.00)	0.44 (0.07)	0.70 (0.07)	0.26 (0.08)	0.75 (0.12)	0.73 (0.14)	**0.88** (0.11)	0.10 (0.04)	*0.00* (0.00)	0.26 (0.10)	0.76 (0.14)
	Montijano	0.28 (0.19)	**0.99** (0.01)	0.52 (0.23)	**0.76** (0.03)	0.26 (0.01)	*0.00* (0.00)	0.41 (0.14)	0.63 (0.05)	0.22 (0.33)	0.75 (0.10)	0.83 (0.12)	0.86 (0.05)	0.07 (0.01)	*0.00* (0.00)	0.39 (0.12)	0.55 (0.09)
	Titania	0.41 (0.14)	0.96 (0.04)	0.49 (0.18)	0.72 (0.09)	0.25 (0.04)	*0.00* (0.00)	0.33 (0.07)	0.77 (0.09)	0.78 (0.12)	0.86 (0.13)	**0.90** (0.04)	0.68 (0.16)	0.13 (0.05)	*0.00* (0.00)	0.29 (0.12)	0.78 (0.21)
	Verato	0.22 (0.09)	0.95 (0.03)	0.53 (0.05)	0.64 (0.05)	0.28 (0.02)	*0.00* (0.00)	0.46 (0.20)	0.79 (0.07)	0.31 (0.25)	0.69 (0.09)	0.50 (0.10)	0.58 (0.01)	0.13 (0.05)	*0.00* (0.00)	0.16 (0.10)	0.73 (0.07)
Vetch	Aitana	0.35 (0.25)	0.90 (0.07)	0.20 (0.02)	0.10 (0.04)	0.41 (0.05)	0.57 (0.32)	0.71 (0.03)	0.33 (0.07)	*0.00* (0.00)	0.24 (0.11)	0.29 (0.05)	0.12 (0.05)	*0.06* (0.09)	**0.73** (0.25)	0.31 (0.18)	0.50 (0.06)
	Alcaraz	*0.00* (0.00)	*0.13* (0.18)	*0.02* (0.02)	0.16 (0.06)	0.37 (0.05)	0.11 (0.09)	0.72 (0.01)	0.21 (0.04)	*0.00* (0.00)	*0.21* (0.20)	*0.02* (0.03)	0.14 (0.05)	0.13 (0.10)	0.54 (0.17)	0.47 (0.15)	0.31 (0.12)
	BGE014897	0.67 (0.21)	0.88 (0.02)	0.08 (0.07)	0.05 (0.03)	0.32 (0.17)	0.46 (0.37)	0.74 (0.01)	0.22 (0.03)	0.77 (0.16)	0.67 (0.06)	0.05 (0.02)	0.18 (0.08)	0.12 (0.13)	0.58 (0.21)	0.63 (0.14)	*0.22* (0.05)
	Castilla	0.30 (0.26)	0.84 (0.14)	0.04 (0.02)	*0.02* (0.02)	0.37 (0.09)	0.44 (0.14)	0.74 (0.03)	0.12 (0.07)	0.80 (0.10)	0.59 (0.15)	0.06 (0.07)	0.09 (0.02)	0.25 (0.21)	0.41 (0.22)	0.40 (0.09)	0.35 (0.06)
	Kira	0.54 (0.12)	0.87 (0.11)	0.12 (0.04)	0.11 (0.01)	*0.12* (0.04)	0.64 (0.24)	0.77 (0.01)	0.35 (0.03)	*0.00* (0.00)	0.51 (0.18)	0.11 (0.04)	0.14 (0.02)	0.08 (0.03)	0.50 (0.14)	0.43 (0.16)	0.38 (0.16)
	Prontivesa	*0.00* (0.00)	0.73 (0.22)	0.13 (0.04)	0.05 (0.04)	0.13 (0.03)	**0.76** (0.27)	0.75 (0.02)	0.19 (0.08)	*0.00* (0.00)	0.28 (0.14)	0.03 (0.02)	0.17 (0.09)	0.12 (0.05)	0.48 (0.26)	0.49 (0.15)	0.33 (0.09)
	Verdor	0.81 (0.09)	0.92 (0.01)	0.03 (0.02)	0.05 (0.01)	0.19 (0.10)	0.67 (0.19)	0.75 (0.02)	0.27 (0.09)	*0.00* (0.00)	0.43 (0.15)	0.03 (0.03)	0.10 (0.02)	0.12 (0.09)	0.62 (0.16)	0.39 (0.26)	0.28 (0.17)

Table 3
Ranked position and values obtained for the species studied according to their suitability to be used in the different cover crops modalities in the seasons 2010–2011 and 2011–2012. B: barley; R: rye; T: triticale; M: mustard; V: vetch. Standard deviations between parentheses. Case letters indicate statistical differences ($p < 0.05$).

Rank	Cover crop	Catch crop	Green manure	Fodder
	2010–2011			
1	**B** 0.89 (0.08) a	**R** 0.74 (0.23) a	**V** 0.58 (0.23) a	**R** 0.79 (0.18) a
2	**T** 0.69 (0.09) ab	**M** 0.64 (0.10) a	**R** 0.54 (0.16) a	**B** 0.59 (0.09) ab
3	**M** 0.69 (0.06) ab	**B** 0.24 (0.08) b	**M** 0.43 (0.08) ab	**T** 0.52 (0.12) b
4	**R** 0.63 (0.11) bc	**T** 0.24 (0.12) b	**T** 0.17 (0.09) bc	**V** 0.37 (0.19) bc
5	**V** 0.39 (0.21) c	**V** 0.22 (0.15) b	**B** 0.11 (0.06) c	**M** 0.23 (0.07) c
	2011–2012			
1	**R** 0.95 (0.05) a	**R** 0.71 (0.01) a	**V** 0.56 (0.23) a	**R** 0.83 (0.02) a
2	**B** 0.92 (0.07) ab	**B** 0.58 (0.19) a	**M** 0.35 (0.20) ab	**T** 0.59 (0.17) ab
3	**T** 0.77 (0.14) ab	**M** 0.48 (0.21) ab	**R** 0.31 (0.02) ab	**B** 0.56 (0.15) ab
4	**V** 0.30 (0.16) bc	**T** 0.46 (0.19) ab	**B** 0.22 (0.15) b	**V** 0.40 (0.20) bc
5	**M** 0.10 (0.15) c	**V** 0.18 (0.12) b	**T** 0.20 (0.12) b	**M** 0.23 (0.24) c

Table 4
Normalized values attained by each cultivar for the specific cover crop functions considered in the seasons 2010–2011 and 2011–2012. Standard deviations between parentheses. Case letters indicate statistical differences ($p < 0.05$). In bold, the maximum values, and in italics, the minimum values.

Species	Cultivars	Cover crop	Catch crop	Green manure	Fodder	Cover crop	Catch crop	Green manure	Fodder
		2010–2011				2011–2012			
Barley	Albacete	0.87 (0.12) ab	0.31 (0.10) c	0.17 (0.10) edc	0.72 (0.08) a	0.96 (0.04) a	0.52 (0.07) abcd	0.15 (0.06) b	0.56 (0.14) abc
	Cierzo	**0.96** (0.03) a	0.21 (0.06) c	0.07 (0.07) e	0.62 (0.07) ab	**0.97** (0.02) a	0.55 (0.17) abcd	0.17 (0.14) b	0.54 (0.12) abc
	CNE 73	0.89 (0.03) ab	0.29 (0.04) c	0.13 (0.03) ed	0.61 (0.08) abc	0.95 (0.01) a	0.76 (0.08) ab	0.35 (0.08) ab	0.59 (0.07) abc
	CNE 81	0.86 (0.02) abc	0.21 (0.15) c	0.10 (0.08) e	0.55 (0.11) abc	0.92 (0.07) ab	0.53 (0.19) abcd	0.17 (0.13) b	0.54 (0.13) abc
	Hispanic	0.90 (0.04) ab	0.25 (0.09) c	0.11 (0.07) e	0.53 (0.06) abc	0.96 (0.05) a	**0.78** (0.20) a	0.36 (0.16) ab	0.69 (0.15) abc
	Tardana	0.96 (0.02) a	0.22 (0.05) c	*0.07* (0.04) e	0.62 (0.04) ab	0.88 (0.06) ab	0.52 (0.31) bcde	0.17 (0.15) b	0.40 (0.22) abc
	V. Alcantara	0.79(0.10) abcd	0.22 (0.10) c	0.10 (0.08) e	0.50 (0.04) abc	0.83 (0.09) ab	0.44 (0.14) cdef	0.14 (0.08) b	0.60 (0.15) abc
Rye	Petkus	0.63 (0.12) cdef	**0.74** (0.23) a	0.54 (0.16) abc	**0.80** (0.18) a	0.95 (0.05) a	0.72 (0.01) ab	0.32 (0.02) ab	**0.83** (0.02) a
Mustard	ssp. mairei	0.69 (0.06) bcde	0.64 (0.11) ab	0.43 (0.08) abc	0.24 (0.07) bcd	0.10 (0.15) e	0.48 (0.21) bcde	0.36 (0.20) ab	*0.23* (0.20) c
Triticale	Forricale	0.67 (0.02) bcde	0.17 (0.07) c	0.11 (0.04) e	0.46 (0.06) bc	0.75 (0.04) abc	0.36 (0.19) bcde	0.15 (0.13) b	0.59 (0.05) abc
	Montijano	0.75 (0.07) abcd	0.19 (0.11) c	0.14 (0.10) de	0.45 (0.09) bc	0.73 (0.17) abc	0.48 (0.15) bcde	0.26 (0.06) ab	0.47 (0.15) abc
	Titania	0.74 (0.12) abcd	0.24 (0.15) c	0.16 (0.12) cde	0.55 (0.17) abc	0.94 (0.05) a	0.70 (0.09) abc	0.34 (0.04) ab	0.77 (0.22) ab
	Verato	0.61 (0.05) def	0.36 (0.04) c	0.28 (0.03) bcd	0.62 (0.08) ab	0.66 (0.14) bc	0.28 (0.06) cde	*0.08* (0.05) b	0.53 (0.10) abc
Vetch	Aitana	0.45 (0.10) fgh	0.37 (0.19) cb	0.73 (0.34) a	0.56 (0.27) abc	0.24 (0.05) e	0.19 (0.02) def	**0.80** (0.26) a	0.74 (0.09) ab
	Alcaraz	*0.05* (0.05) i	*0.04* (0.06) c	0.26 (0.08) cde	*0.10* (0.09) d	0.14 (0.11) e	*0.06* (0.04) f	0.52 (0.11) a	0.34 (0.16) abc
	BGE014897	0.50 (0.05) efg	0.34(0.08) cb	0.58 (0.22) abc	0.34 (0.15) bcd	0.52 (0.10) dc	0.35 (0.10) bcde	0.61 (0.39) ab	0.29 (0.27) bc
	Castilla	0.35 (0.14) gh	0.28 (0.10) c	0.57 (0.08) abc	0.25(0.09) bcd	0.54 (0.03) c	0.34 (0.02) bcde	0.45 (0.27) ab	0.37 (0.15) abc
	Kira	0.48 (0.09) fgh	0.26 (0.05) c	0.67 (0.19) ab	0.49 (0.011) abc	0.27 (0.09) ed	0.14 (0.02) def	0.51 (0.16) ab	0.41 (0.13) abc
	Prontivesa	0.24 (0.06) hi	0.17 (0.06) c	**0.79** (0.21) a	0.45 (0.17) abc	0.17 (0.03) e	0.07 (0.05) f	0.47 (0.22) ab	0.32 (0.24) bc
	Verdor	0.72 (0.03) edcb	0.05 (0.02) c	0.49 (0.14) bcd	0.43 (0.15) abc	0.22 (0.05) e	0.09 (0.11) ef	0.58 (0.20) ab	0.37 (0.09) abc

Table 5
Ranked position attained by each cultivar for the specific cover crop functions considered in the seasons 2010–2011 and 2011–2012. B: barley; R: rye; T: triticale; M: mustard; V: vetch.

Rank	Cover crop	Catch crop	Green manure	Fodder	Cover crop	Catch crop	Green manure	Fodder
	2010–2011				2011–2012			
1	Cierzo B.	Petkus R.	Prontivesa V.	Petkus R.	Cierzo B.	Hispanic B.	Aitana V.	Petkus R.
2	Tardana B.	Ssp. mairei M.	Aitana V.	Albacete B.	Hispanic B.	CNE 73 B.	BGE014897 V.	Titania T.
3	Hispanic B.	Aitana V.	Kira V.	Cierzo B.	Albacete B.	Petkus R.	Verdor V.	Aitana V.
4	CNE 73 B.	Verato T.	BGE014897 V.	Verato T.	Petkus R.	Titania T.	Alcaraz V.	Hispanic B.
5	Albacete B.	BGE014897 V.	Castilla V.	Tardana B.	CNE 73 B.	Cierzo B.	Kira V.	V. Alcántara B.
6	CNE 81 B.	Albacete B.	Petkus R.	CNE 73 B.	Titania T.	CNE 81 B.	Prontivesa V.	Forricale T.
7	V. Alcántara B.	CNE 73 B.	Verdor V.	Aitana V.	CNE 81 B.	Albacete B.	Castilla V.	CNE 73 B.
8	Verdor V.	Castilla V.	Ssp. mairei M.	Titania T.	Tardana B.	Tardana B.	Ssp. mairei M.	Albacete B.
9	Montijano T.	Kira V.	Verato T.	CNE 81 B.	V. Alcántara B.	Montijano T.	Hispanic B.	Cierzo B.
10	Titania T.	Hispanic B.	Alcaraz V.	Hispanic B.	Forricale T.	Ssp. mairei M.	CNE 73 B.	CNE 81 B.
11	Petkus R.	Titania T.	Albacete B.	V. Alcántara B.	Montijano T.	V. Alcántara B.	Titania T.	Verato T.
12	Forricale T.	V. Alcántara B.	Titania T.	Kira V.	Verato T.	Forricale T.	Petkus R.	Montijano T.
13	Ssp. mairei M.	Tardana B.	Montijano T.	Forricale T.	Castilla V.	BGE014897 V.	Montijano T.	Kira V.
14	Verato T.	CNE 81 B.	CNE 73 B.	Montijano T.	BGE014897 V.	Castilla V.	Cierzo B.	Tardana B.
15	BGE014897 V.	Cierzo B.	Forricale T.	Prontivesa V.	Kira V.	Verato T.	CNE 81 B.	Verdor V.
16	Kira V.	Montijano T.	Hispanic B.	Verdor V.	Aitana V.	Aitana V.	Tardana B.	Castilla V.
17	Aitana V.	Forricale T.	CNE 81 B.	BGE014897 V.	Verdor V.	Kira V.	Albacete B.	Alcaraz V.
18	Castilla V.	Prontivesa V.	V. Alcántara B.	Castilla V.	Prontivesa V.	Verdor V.	Forricale T.	Prontivesa V.
19	Prontivesa V.	Verdor V.	Cierzo B.	Ssp. mairei M.	Alcaraz V.	Prontivesa V.	V. Alcántara B.	BGE014897 V.
20	Alcaraz V.	Alcaraz V.	Tardana B.	Alcaraz V.	Ssp. mairei M.	Alcaraz V.	Verato T.	Ssp. mairei M.

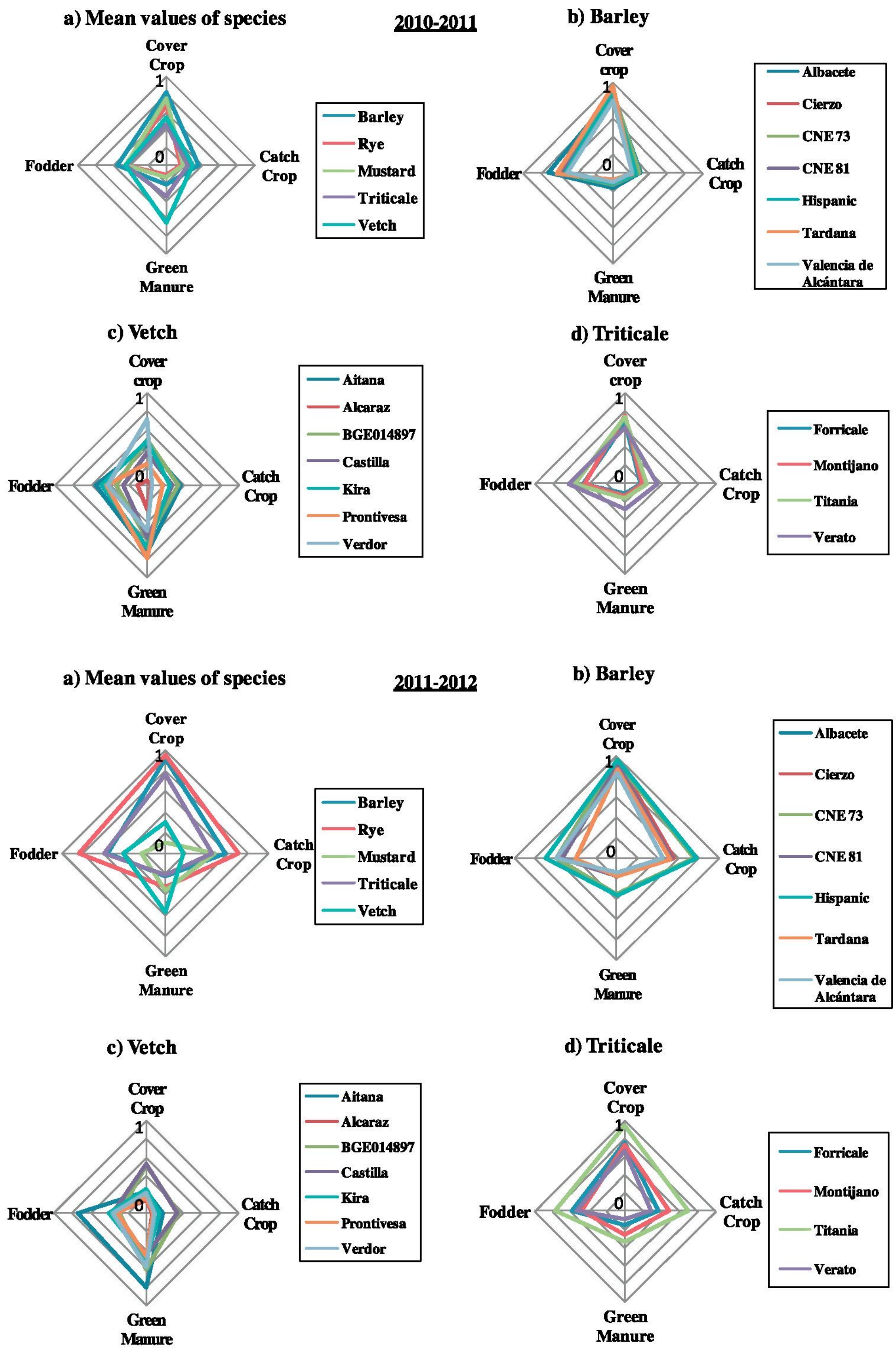

Fig. 3. Normalized mean values attained for the two seasons studied (2010–2011 and 2011–2012) in the utility functions of the cover crop modalities defined in the text for (a) the average value of the cultivars within each species, and the different cultivars of (b) barley, (c) vetch and (d) triticale.

in the second season, and, as a consequence GC and BM were highly diminished. In fact, similar attributes have been proposed in previous studies comparing the ability of several species to act as cover crops (Bodner et al., 2010; Ramírez-García et al., 2015). The GC attribute was particularly interesting because allowed to monitoring crop evolution base on non-destructive measurements. The rest of the attributes determined at harvest provide a good characterization of agronomical particularities of the cultivars and their chemical composition. This work focused on the above ground growth of cover crops; however, the characterization could be complemented with information from the root system and from soil samples at harvest, particularly when studying the ability to act as a catch crop or if soil water extraction is a relevant issue (Thorup-Kristensen et al., 2001; Merrill et al., 2002).

The grasses had a good establishment in the field and a fast growth allowing the rapid coverage of the ground along the two seasons. The attribute GC of the grasses attained therefore elevated values and as expected, the three species showed a high aptitude as cover crops. Their values were almost independent from the adverse climatic conditions produced during winter frosts. On the contrary, the mustard subspecies selected, whose origin is a warmer Mediterranean area than Madrid, was seriously affected by winter frosts and the plants were almost destroyed during the 2011–2012 winter. Due to this lack of cold hardness, mustard results presented the most relevant differences between years of all the studied crops, attaining similar levels to the grasses in the first season and to vetches in the second. As expected, this was the species with the highest N_{upt} and RQ (Chaves et al., 2004; Gallejones et al., 2012). At last, the Rye, which worst overall rank was 12 (Table 5), showed very good conditions to be used as catch crop and fodder as a result of its high tolerance to frosts, the big amount of biomass that accumulates and the concentrations of C, N and dietary fibers that presents. The utility functions which showed more different results between the years were the ones of the cover and catch crop modalities, while the green manure and especially fodder results were more stable. This is due to the higher weight of the attributes related to growth characteristics (GC and BM) in Eqs. (3) and (4) compared to the ones expressing its nutrient and fibers content (i.e. CN, N_{upt}, N_{dfa}, RQ and DFC), which are of bigger importance in Eqs. (5) and (6) and not influenced by weather conditions.

The grasses had a good establishment in the field and a fast growth allowing the rapid coverage of the ground along the two seasons. The attribute GC of the grasses attained therefore elevated values and, as expected, the three species showed a high aptitude to use them as cover crops. Their values were almost independent from the adverse climatic conditions during winter frosts. The barley cultivars fastest in covering the ground were the more suitable as cover crops. The rye showed very good conditions to be used as a catch crop and fodder as a result of its high tolerance to frosts, the big amount of biomass that accumulates and the dietary fibers content. The mustard was very suitable as a catch crop in warmer years, but due to lack of cold hardness it was killed by the winter frosts in 2012. The mustard subspecies selected was original from Andalusia (Alcántara et al., 2009), a warmer Mediterranean area than Madrid, so the result is not surprising. Some authors proposed frost killing as a natural way of terminating cover crops, saving herbicide application or plowing (Thorup-Kristensen et al., 2003). We did not consider this attribute in our study but it could be interesting in future research. In any case, our results agree with the literature in the high potential of mustard as a catch crop if it is properly established, being the crop with the highest N_{upt} and RQ (Chaves et al., 2004; Gallejones et al., 2012). There was a large variability between vetch cultivars performance for the different cover crop usages, showing that there is room for breeding varieties adapted to the several cover crop uses. It is remarkable that the variety BGE014897 showed a high aptitude as a cover crop in both seasons, particularly due to the fast establishment in the field (high GC values in Table 2). This variety is an original entry from the CRF and is not commercialized, and it could be interesting to use it as a cover crop. There were also differences in N derived from the atmosphere, originated from both, the δ15N and the biomass accumulated. Similar differences between the legume atmospheric N fixing capabilities have being reported and showed the opportunity for improving legumes to act as green manure (Unkovich and Pate, 2000). In general, the cover and catch crop utility functions showed more different results between years than the green manure or fodder. This occurred because the weight of the attributes related to growth characteristics (GC and BM) was higher in Eqs. (3) and (4) than in Eqs. (5) and (6). In these last crop utility functions (Eqs. (5) and (6)) the attributes expressing crop nutrient and fiber content (i.e. CN, N_{upt}, N_{dfa}, RQ and DFC) had more relevance, and were little affected by weather conditions as observed by other researchers (Quemada and Cabrera, 2002).

The results obtained in this work justify the MCDA approach applied, the weighted average method. As Guitouni and Martel (1998) pointed out, many analysts and researchers are incapable of justifying clearly their choice of one MCDA method. Comparing species and cultivars is a discrete problem because it has a limited number of solutions, and being involved various attributes needs a method that allowed for flexible weighing. The weighted average approach suited to this goal, because allowed aggregation of multiple criteria into utility functions and flexibility in the relative weights of the criteria (Hayashi, 2000). The different species and cultivars were properly evaluated and compared for its use as cover crops in any of the modalities presented. The ranked of the species and the cultivars obtained is logical according to the state of the art and might be useful for the decision taking, as the solutions provided have a clear preferential interpretation. The climatic variability effect was also expressed by the results, and the ranks of the cover crop modalities less dependent on climatic variables did not vary between years. This work does not aim to describe all the possible reasons for the rankings obtained, but rather supply with a tool to researchers interested in developing other utility functions involving variables or attributes that might be relevant to select crops for specific functions. The method used is simple and intuitive, what permits the easy handling of decision makers not familiarized with MCDA or statistical analyses. The design of the utility functions and the weights of the attributes are subjective components that might be considered as a weak point of the method and a matter of discussion (Betrie et al., 2013). However, at the same time they allow the decision makers to perform modifications, adapting the methodology to their particular interest. In this study, the relative weights of the criteria were provided by the authors of this paper, acting as decision makers.

Another function of cover crops is weed control (Ross et al., 2001). Provision of an early soil cover reduces the establishment of seedlings and the growth of the established weeds is reduce through competitive suppression. Generally soil cover rate and cover crop biomass accumulation are found crucial factors determining the weed suppressive ability even if there might be other specific mechanisms involved as alelopathic interactions, (Den Hollander et al., 2007). Therefore, weed control could be included in a MCDA by incorporating a utility function similar to erosion control and, if necessary, adding a term related to a specific weed suppression mechanism involved. In our experiment, this function was excluded and weeds were removed by hand to highlight the potential of the studied species. A drawback of this approach is that the performance of cover crops less competitive with weeds (i.e. legume and mustard) was probably favored.

Cover crop mixtures is known to be an efficient technique to merge benefits of the individual species (Tosti et al., 2014). Cover crop species ranking may allowed to choose the species characteristics for making optimal mixtures, giving the chance to both species to succeed without too much dominance of one species on the other. For instance, a grass species that covers the ground fast and scavenges the soil N is suitable to mix with a competitive legume, one that is also able to cover the soil relatively fast and fixed atmospheric N_2. If the legume species is not competitive, it might suit better with an early emerging grass that has a slow initial growth rate, so it leaves space for the legume to grow. Moreover, by mixing species with complementary residue quality it can be expect to control N release and avoid pre-emptive competition with the subsequent cash crop (Alonso-Ayuso et al., 2014).

The polar plots give an overview of the four cover crop modalities at the inter- and intra-species levels, allowing the comparison within alternatives and showing the weak and strong points of a particular species or cultivar. This type of plots may help the breeders to identify the variety they are looking for, and the farmers to adapt their cover cropping practice to the specific conditions of an agrosystem (soil type, economic viability of cover cropping, etc.). The farmer will have more information to decide which alternative to use according to the cover crop particular features and the aspects that wants to improve in the agrosystem.

5. Conclusions

Multicriteria decision analysis (MCDA) allowed the evaluation of different species and cultivars according to their suitability to be used as cover crops in the specific modalities of cover crop, catch crop, green manure and fodder. The grasses were the most valuable species for the cover crop, catch crop and fodder uses, especially the rye which attained top positions in the three modalities. The capability of vetches to fix N from the atmosphere explained their suitability to be used as green manures. Weather had a strong effect on the mustard and vetch performance, but the mustard attained high ranks as cover and catch crop when growth conditions were favorable. Hispanic was the most outstanding barley cultivar in all the cover crop modalities assessed except for the fodder. Similar to barleys but attaining generally lower ranks, the triticales performed better as cover crop and fodder, being Titania the cultivar that perform the best. There was a large variability between vetch cultivars performance, having Aitana and BGE14897 balance aptitudes as cover, catch crop and green manure. The MCDA permitted the aggregation of a set of variables of different types and showed potential to be adapted to cover crop ranking for different modalities. The graphic representation of the cover crop utility functions provided an overview of the alternatives and shows the weak and strong points of a particular species or cultivar.

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